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QUANTUM THEORY OF EXTENDED PARTICLES

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Abstract

The paper presents some preliminary thoughts on a quantum field theory for extended particles. The theory of relativity demands that particles with non-zero spin have finite extentions, so point particle theories are at best approximate. By introducing a deformation, rotation can be made to provide the spin and a force to balance an attractive interaction. The strength of the gravitational interaction must be modified at short distances in order to outweight the electromagnetic repulsion. An alternative is to view this as a strong interaction operative for both leptons and baryons. Two intrinsic frames of reference may be introduced: one based on a tetrad of fixed orientation following the centre of momentum, and one body-fixed tetrad following the rotation. The relationship between bare mass, mass in the body-fixed frame and rotational energy is discussed. A Lagrangian or Hamiltonian based field theory is obtained by interpreting standard wave functions as representing actual matter distributions rather than probability amplitudes for point objects.

1. Introduction

The point particle approximation has gained a fundamental role in physical theory. In classical mechanics, the point approximation to celestial bodies was a matter of convenience. No one doubted that these bodies in reality have finite extentions. The same attitude towards the point particle approximation may have prevailed during the early times of quantum mechanics, despite the irreconcilability between the probabilistic interpretation of the wave function and any departure from a point particle picture. For example, estimates of the electromagnetic self energy of the electron usually assumed an extended charge distribution. Most current field theories for elementary particles, such as the standard model comprising electroweak and color dynamics[1], demand a rigorous point particle description of all fundamental particles. An exception is the superstring theory[2], which assumes that fundamental particles have a linear extention. In summary, the point particle approximation is no longer made for reasons of convenience, but when made, it constitutes a fundamental assumption regarding the constitution of matter.

Relativistic theory demands that every object with an intrinsic angular momentum (spin) has a finite extention. To see this one may consider the position of the centre of mass in different Lorentz frames. It will lie on a circular disc with radius $r_{C.M.}$, and if one demands the mass density to be everywhere positive, then the density must extend to radii beyond the centre of mass disc[3]:

$$r \geqslant r_{C.M.} = |\vec{s}|/(m_o c) = 3^{1/2}\hbar/(2m_o c) \qquad (0)$$

This amounts to about 3×10^{-13}m for an electron, i.e. two orders of magnitude larger than the classical electron radius $e^2/m_o c^2$.

Any realistic relativistic quantum thory of elementary particles with spin must then take into account the finite extentions of the particles, at least in situations where short distances are involved. Several attempts have been made to formulate such theories[4,5], but the results have been limited. The most successful attempt is that of the recent superstring theory[2], which by departing from the point particle picture at short distances (corresponding to Planck-energy interactions) avoids the infinities of the standard model. The superstring theory unifies all four basic interactions, but relegates much of the physics to six new space-time dimensions. Spin is still treated as an "intrinsic property", for which no physical explanation is given. The following represents an attempt to outline some general features of a quantum theory of extended particles. It departs in several ways from the previous approaches.

A basic problem in a quantum description of an extended particle is, that the absolute square of a wave function $\psi(x_\mu)$ cannot be interpreted as the probability for finding the particle at $x_\mu(\mu=1,2,3,4)$. It is tempting to interpret $\psi^*\psi$ as being proportional to the actual matter density. The momentum distribution defined by the Fourier transform of the (entire) matter distribution will then be unrelated to the local momenta at specific positions within the matter distribution. The momenta associated with the local elements of matter will be totally indetermined. Still, canonical quantization using $p_\mu \rightarrow -i\hbar\partial_\mu$ may lead to acceptable equations of motion.

The program I shall follow is to first make an (eventually approximate) separation between the motion of the centre of momentum of the entire extended particle and its intrinsic motion. Next, the intrinsic motion will be described in a rotating (and hence accelerated) coordinate system, in order to obtain the spin in a way, which leads to conventional spinor description in the external frame, while eliminating spin degrees of freedom from the treatment of the internal motion in a body-fixed frame (except for possible coupling effects). The idea is to allow conventional theories of elementary particles to remain applicable to the motion of the centre of momentum, except when so short distances are involved, that couplings to the intrinsic motion cannot be neglected.

According to the principle of general relativity, any interaction which may accelerate elements of matter can be "transformed away" by a suitable choice of curved space metric. The Einstein equations demonstrate how this can be done for non-quantum gravitational interactions. It is not known how to do this for electromagnetic, weak and strong interactions in a general quantum theory, and since such non-gravitational interactions are important for the internal structure of elementary particles, I shall choose to remain in ordinary flat-space metric and include the various interactions explicitly.

2. Internal motion and spin

The total 4-momentum for an extended particle may be obtained from the 4-momentum density by

$$P_\mu = \int p_\mu \, d^3x \tag{1}$$

The centre of momentum frame is defined as one in which the spatial part of P is zero, $P = (0,0,0,mc)$. If the extended particle can be treated as an isolated system, then the motion of its centre of momentum (CM) is that of a free particle, given e.g. by the standard Dirac equation. The relativistic but non-quantal Hamilton function may be written

$$H = \left(H_{intr}{}^2 + c^2 P_{CM}{}^2 \right)^{1/2} \tag{2}$$

where $H_{intr} = mc^2$. If the extended particles interact with other particles or fields, then an approximate separation between intrinsic and CM motion may be achieved by simply retaining the value mc^2 for H_{intr}, in whatever extention of the free particle equation of motion one chooses to use, e.g. when a gauge potential is added to P:

$$(\gamma_\mu(P^\mu+A^\mu)+mc)\Psi = 0 \qquad (3)$$

where Ψ is a 4-component wave function.

I now introduce a rotating frame, which I shall denote the body-fixed frame, because it could be associated with a tetrad following the rotation of a deformed particle in such a way that no gross rotation is present when viewing the system from this intrinsic frame. The Hamilton function in the body-fixed frame, H_{bff}, may be introduced by

$$H_{intr} = ((H_{bff}-V_{intr})^2 + H_{rot}{}^2)^{1/2} + V_{intr} \qquad (4)$$

where the proper mass remaining after the rotation has been taken out may be denoted $M=H_{bff}/c^2$. The rotational Hamilton function can be written[5]

$$H_{rot} = \frac{\hbar^2}{2I}\, s(s+1) \qquad (5)$$

where s (=1/2 for the electron) is the spin quantum number and I the moment of inertia of the extended particle.

Hara and Gotō have shown[5], that the external motion of the quantized, relativistic rotation of a free, extended particle is a straightforward generalization of the Dirac equation to general spin s. They further interpret the quantum number which in the non-relativistic limit corresponds to the projection of the spin on the intrinsic 3-axis (assumed to be a symmetry axis) as the baryon or lepton number, because its two values correspond to the positive and negative energy solutions of the ordinary Dirac equation.

It is often believed, that the rotation of a spherically symmetric object in quantum mechanics is uninteresting or impossible, and since it may seem appropriate to assume that fundamental particles such as the electron are spherically symmetric, then the introduction of a non-zero moment of inertia I may appear unwarranted. Rotation by an angle ω_1 about a certain axis is given by

$$R(\omega_1)\psi = e^{i\alpha(\omega_1)}\psi = e^{-i\omega_1 S_1/\hbar}\psi \qquad (6)$$

where S_1 is the component of the angular momentum operator along the axis of rotation. If the system is symmetric about this axis, then $\alpha(\omega_1)$ is a c-number (the gauge angle). S_1 and ω_1 are conjugate variables satisfying an uncertainty relation of the form

$$\sigma(S_1)\cdot\sigma(\omega_1) \gtrsim \hbar/2 \tag{7}$$

As S_1 can only take half integer values 0,1/2,1,3/2,..., then our inability to tell is the system is rotated ($\sigma(\omega_1) \sim \pi$) implies that the spin is at least $\hbar/2$. This again forces the conclusion that the moment of inertia is non-zero, i.e. that the system must be deformed, although the deformations may average out over extended periods of time. The uncertainty principle makes it possible, that the system has some deformation, but that any attempt to measure it (e.g. by cranking the system by a certain angle ω_1) will destroy all information about the spin component S_1. The fact that e.g. the electron does not exhibit any rotational spectrum on top of the s=1/2 ground state tells us that either I is very small or the coupling between intrinsic and rotational motion is very strong.

The Hamilton function in the body-fixed frame may take the form

$$H_{bff} = (b^2c^4+c^2P_{bff}{}^2-H_{rot,intr}{}^2)^{1/2} + V_{bff} \tag{8}$$

where b is the bare mass, P_{bff} a momentum variable in the body-fixed frame and $H_{rot,intr}$ represents the centrifugal and Coriolis effects of the rotation as manifested in the body-fixed frame. The quantum mechanical version of this equation may be taken as a Klein-Gordon type wave equation.

considering that the Dirac type doubling of dimensions is not required once the spin degree of freedom has been treated explicitly.

$$D_\mu D^\mu \Phi + b^2 c^4 \Phi = H^2_{rot,intr}\Phi \tag{9}$$

Here D^μ includes the potential terms,

$$D^\mu = -ic\hbar\partial^\mu + A^\mu \tag{10}$$

for example with

$$A^\mu = b^2 \left(\varkappa_g A_g^\mu + \varkappa_{em} A_{em}^\mu + \varkappa_s A_s^\mu\right) \tag{11}$$

The gravitational potential (A_g) and a short range potential (A_s) may be taken as time-like. A_{em} represents the electromagnetic interaction. One may also look at A^μ as <u>one</u> potential with a more complicated radial dependence. It is straightforward to write the Lagrangian density from which Eq. (9) may be derived, and to complement it with the usual quadratic terms in the fields $F^{\mu\nu}=\partial^\mu A^\nu-\partial^\nu A^\mu$. The usual second quantization procedure introduces boson gauge particles and allows for perturbation expansion of solutions.

Three mass parameters for the extended particle have been introduced: b is the bare mass corresponding to dispersing the constituent matter to infinity. Taking into account the binding potentials and the non-rotational kinetic energy in the intrinsic motion of the extended particle in the body-fixed frame, at least one state of lower mass M should be obtained. This mass is raised to the observed mass m by the effect of the rotation (spin energy). It is expected that m will lie between M and b, because else the system would not remain together during rotation. The case of a small moment of inertia discussed above would then have the proper mass of the spin-3/2 excited rotational state of a spin-1/2 particle above b. If instead the rotational excitation energies were small compared with $b-M$, then one would expect the spin-3/2 state to be bound and in the observable mass regime, despite the perturbing effects of the coupling between intrinsic and rotational motion. I shall therefore assume that I is small.

3. Mass estimates

In order that Eq. (9) shall have solutions corresponding to bound systems (i.e. the extended elementary particles), the potentials must furnish an attraction at short ranges. If charge is distributed in the same way as the matter constituting the particle, then the net effect of the gravitational and electromagnetic forces will be repulsive for matter with a uniform charge sign. Hence a strong interaction must deliver the attraction, and there must be a strong interaction component also for leptons, in order to account for their internal constitution (yet this component has to become quenched externally, as leptons are not known to interact strongly with other particles). The centrifugal force represented by $H_{rot,intr}$ acts to prevent the density within the extended particle from rising. One may visualize the process of forming an elementary particle as starting with dispersed matter, which is eventually accreted by the strong interactions. As the proto-particles and antiparticles shrink, they may annihilate into photons, as long as their energy remains positive. Assuming the interaction to be sufficiently strong, the energy will from a certain stage become negative, implying that excess energy cannot be emitted as light. Instead, it has to be transformed into rotational energy, and the shrinking (collapse) of the proto-particle is eventually stopped when the centrifugal and strong forces balance. In order to calculate this process for leptons, an electromagnetic field term has to be added to Eq. (9). Similar remarks pertain to baryons such as quarks, where QCD terms describing the quark-gluon fields and interactions have to be introduced in Eq. (9).

The following discussion will be restricted to leptons, and in particular to the electron. Rather than solve the equation of motion, I shall make some general remarks on the energy solutions, based on Eq. (4). For a particle with a given spin s, this equation reads

$$m(s)c^2 = \left((Mc^2-V)^2 + (\frac{\hbar^2}{2I}\, s(s+1))^2\right)^{1/2} + V \qquad (12)$$

where just V is written instead of V_{intr}.

In order to make the kinetic energy in the body-fixed frame positive, the inequality

$$Mc^2 > bc^2 + V \qquad (13)$$

must hold. Furthermore, I shall assume that the s=3/2 rotational state is unbound, so that

$$m(3/2) \gtrsim b \qquad (14)$$

The fact that no excited spin-3/2 electron state (nor any rotational band of any lepton) has been observed, of course only guarantees that its energy is below the present detection limit, which could be substantially lower than b. Yet the case of only one bound state is an interesting case. The two equations (12) for s=1/2 and 3/2, together with the inequalities (13) and (14), allow limits for V, I and M to be determined as function of b.

I first look at the case where b equals the Planck mass. In this case the limit on V becomes

$$V < -1.06\ bc^2 = -2.08 \times 10^9\ \mathrm{J} \qquad (15)$$

and the other limits $I \lesssim 5.91\times10^{-78}\mathrm{kgm}^2$ ($\hbar^2/2I \gtrsim 0.942\times\mathrm{GJ}$) and $Mc^2 \lesssim -0.124$ GJ. The limit on the moment of inertia is very close to the Planck moment of inertia ($\mu_P\lambda_P{}^2 = 5.69\times10^{-78}\mathrm{kgm}^2$). The angular frequency defined by $\omega = \hbar(s(s+1))^{1/2}/I$ equals $1.55\times10^{43}\ \mathrm{s}^{-1}$, so that the classical radius r_c for which ωr_c reaches c becomes 1.94×10^{-35}m, which again equals the Planck radius to within 20%. The value found for the potential depth V is of the same order of magnitude as the equivalent number for the strong interaction between baryons[6].

This example indicates, that in order to get a spin of $\hbar/2$, the bulk matter of an extended particle with bare mass equal to the Planck mass has to be confined to a deformed sphere of radial dimension equal to the Planck length, and to rotate in a way which in a classical picture is highly relativistic. However, before discussing the implications of the model further, bare masses different from the Planck mass should be considered.

Fig. 1 shows the rotational energy and the energy Mc^2 as function of bc^2, obtained for a strong potential V fixed at the value estimated in the example above as a limit allowing the bare mass to take any value up to the Planck mass 2.18×10^{-8}kg. Fig. 2 shows m (short for $m(1/2)$) and M in units of the bare mass. For bc^2 above 2×10^{-12}, M is negative and only the rotational energy brings the observed mass up above zero. Only for smaller b does M become positive and close to m (both approach the bare mass). The rotational energy changes less than the energy in the body-fixed frame (Fig. 1).

The fact that M becomes negative means that one no longer can be sure that the energy density is everywhere positive, as required in order to call upon the Møller expression, Eq. (0), for concluding that the matter distribution extends beyond a certain radius. The particles may be much smaller than the Møller radius, which is already at variance with observed limits on lepton radii[7]. However, this does not destroy the argument against point particles, because any particle energy density would become positive if it were shrinked towards a point. It is also seen, that for the small b's that do give positive M, the energy density is indeed positive and Eq. (0) should hold (in this case it does not matter whether m or M is inserted, because they tend to be of similar magnitude). The Møller radius is much larger than the radius r_c (here some 10^{-24} to 10^{-23}), for which the classical rotational velocity at the periphery reaches the speed of light.

The linear relationship between I and r_c implies that the system cannot be interpreted as a classical rotor (for which $I \sim R^2$). The linear moment of inertia may arise from a surface deformation, if the deformation diminishes with increasing radius. The classical value derived from the data of Fig. 1 implies a huge deformation in the limit $b \sim m$. Only near the limit of the bare mass equal to the Planck mass will the implied deformation be of the order of or small compared to unity. This strongly suggests that physically relevant theories should assume bare particle masses in the vicinity of the Planck mass (as e.g. the superstring theories do).

To determine the correct value of the bare mass, a proper solution of the equation of motion must be performed. Regular solutions can be found only for some values of b, due to the presence of different powers of the wave function Φ in Eq. (9). The three kinds of potentials A_μ all depend on $|\Phi|^2$. For instance, the scalar gravitational potential would in a coordinate representation be

$$A_g^4 = -\frac{G\,m^2}{\varkappa_g b^2}\int \frac{|\Phi(\vec{r}\,',t-|\vec{r}-\vec{r}\,'|/c)|^2}{|\vec{r}-\vec{r}\,'|}d^3r' \qquad (16)$$

4. Conclusion

This paper has shown that it is possible to describe extended particles by a modified version of standard quantum theory. The modification is that wavefunctions are interpreted as representing the real matter amplitude rather than just a probability amplitude. The mass density is in the modified theory proportional to the absolute square of the wave function. Despite this, the bulk motion of the centre of momentum of the extended particle for an isolated system may be described by the usual quantum theory, and the probabilistic interpretion of the CM wave function can be maintained, due to the canonical relationship between coordinate and momentum (conventional Fourier transformation, commutator and uncertainty relations)[8]. If the extended particle is not isolated, these remarks are valid only insofar as coupling between CM and internal motion can be neglected. This limits the use of conventional field theories for extended particles.

As regards the intrinsic motion within the extended particle, the relationship between rotation and spin has been looked into, and energy/mass relations have been derived by demanding that the spin-1/2 lowest state should be bound, but the first (spin-3/2) rotationally excited state unbound.

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Figure captions:

FIG.1. Bare-mass dependence of rotational ($\hbar^2/2I$) and non-rotational (Mc^2) energy of an extended particle. For very small bare masses, M becomes positive (dashed line). A fixed strong potential V has been assumed.

FIG. 2. Total mass (m) and non-rotational mass (M) of an extended particle in its ground state, as function of the bare mass (b). The strong potential is fixed.

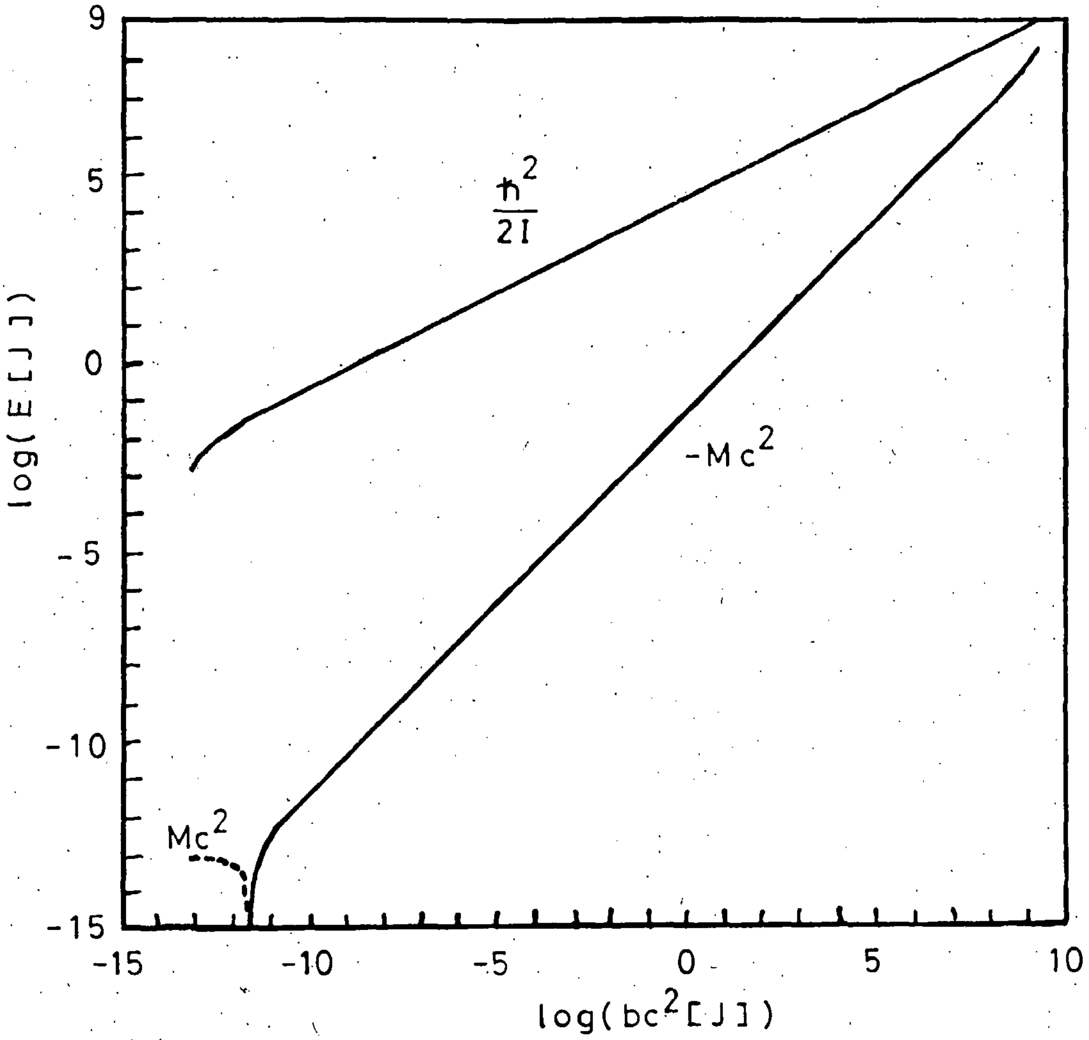

FIG. 1

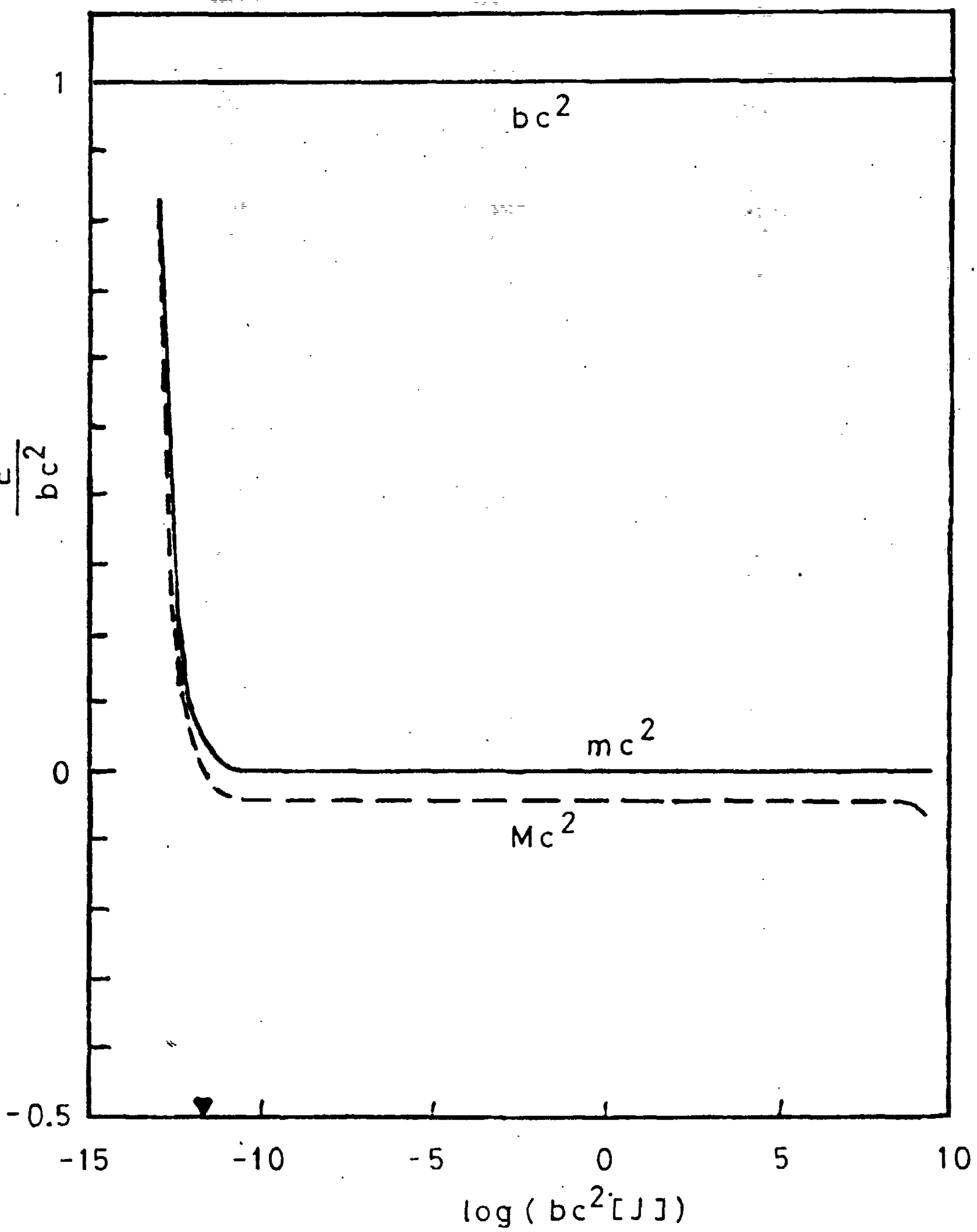

FIG. 2

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